NASA TECHNICAL TRANSLATION

NASA TT F-323

NASA TT F-323

SCATTERED AND TOTAL SOLAR RADIATION UNDER VARIOUS CONDITIONS

by B. M. Gal'perin and L. P. Seryakova

From *Trudy Glavnoy Geofizicheskoy Observatorii imeni A. I. Voyeykova,* No. 152, 1964

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1965

NASA TT F-

SCATTERED AND TOTAL SOLAR RADIATION UNDER VARIOUS CONDITIONS

B. M. Gal'perin and L. P. Seryakova

Translation of "Rasseyannaya i summarnaya solnechnaya radiatsiya pri razlichnykh usloviyakh." Trudy Glavnoy Geofizicheskoy Observatorii imeni A. I. Voyeykova, No. 152, pp. 96-109, 1964.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Office of Technical Services, Department of Commerce, Washington, D.C. 20230 -- Price $1.00

SCATTERED AND TOTAL SOLAR RADIATION UNDER VARIOUS CONDITIONS

B. M. Gal'perin and L. P. Seryakova

ABSTRACT

An investigation was made of the effect of shape and number of clouds as well as of the state of the solar disk on the intensity of scattered and total solar radiation. The results may be used to evaluate the incident radiation for various altitudes of the sun and under various meteorological conditions.

Magnitudes of solar radiation intensity under various meteorological conditions are necessary to solve various problems--calculations of the diurnal variation in the components of the thermal balance of the active surface, investigation of the transformation of air masses, evaluation of natural illumination, etc. However, the collected experimental data have not been sufficiently processed and generalized. The data available in the literature on this question refer primarily to cloudiness of 10 points. Thus, M. S. Temnikova (ref. 8), based on observations conducted at Pyatigorsk, obtained average values of the scattered radiation under substantial cloudiness of various forms. N. N. Kalitin (ref. 6) used the data recorded at Pavlovsk to determine the average value of direct, scattered and total solar radiation for various clouds, when cloudiness was 10 points. Similar data, but only for total radiation, have been presented by B. Haurwitz (ref. 9), based on observations at Blue Hill Observatory. The special features of total and scattered radiations in the Arctic under cloudiness of 10 points are considered by B. M. Gal'perin (ref. 4). The effect of the quantity of clouds of various shapes on the intensity of scattered radiation was first investigated by M. V. Gushchina (ref. 7). However, due to the inaccuracy of the N. N. Kalitin pyranometer used at that time at Pavlovsk, the values he obtained are low. Recently Ye. T. Barashkov (ref. 1) obtained similar data; based on measurements at Karadagh, however, these were obtained as the average of three formations rather than from individual cloud shapes.

The purpose of the present work is to investigate the effect of the shape, and number of clouds and of the intensity of solar radiation on the magnitudes of total and scattered solar radiation. For this purpose we used the results of the standard measurements of total and scattered solar radiation during the snow-free period (April-October) at the following stations: Voyeykovo (1953-1959), Tartu (1953-1960), Riga (1953, 1955-1958, 1960) and Minsk (1953-1960). The analysis carried out during the processing of the data has shown that for the same altitude of the sun, the shape and quantity of clouds and the intensity of solar radiation there is no difference in the intensity of radiation at various stations. This has made it possible to correlate the results.

The material was processed graphically: for each shape and quantity of clouds and intensity of solar radiation ($\odot^2$, $\odot$, $\odot^0$, Π) the data of standard observations were used to construct empirical graphs, showing the variation in total and scattered radiation as a function of the altitude of the sun. Since the visual determination of the number of clouds is approximate, the graphs were constructed for the following groups: 2-3, 4-5, 6-7, 8-9, $\boxed{10}$ and 10 points. Because the transparency of the atmosphere, the vertical power of the clouds and their liquid water content vary during the period of the year, the graphs $Q_0 = f(h_\odot)$ for the cloud-free sky were constructed for different months, while the curves $Q = f(h_\odot)$ and $D = f(h_\odot)$ for the case when clouds were present were constructed by seasons: spring (April-May), summer (June-August) and fall (September-October).

Some clouds are seldom encountered alone or are primarily observed in a definite quantity. For example, Ac and Sc without "a mixture" of other clouds are encountered most frequently during extensive cloudiness; therefore, when the cloudiness is less than 8-9 points, the observations with Ac and Sc were combined to obtain the values of scattered and total radiation during "wavy" clouds.

During substantial convective cloudiness (8-9 and 10 points) Cb predominate, while for lesser cloudiness Cu predominate. Usually, Cb are accompanied by other cloud shapes: when cloudiness is 6-7 and 8-9 points, a combination of Cb and Cu is encountered and when the altitudes of the sun are low, Sc predominate.

With a cloudiness of $\boxed{10}$ and 10 points, two groups were considered independently: Cb predominate (Cb; Cb, Frnb; Cb, Cu; Cb, Sc; Cb, Ac) and Cb do not predominate (Sc, Cb; Cu, Cb; Ac, Cb).

In addition to the principle cloud shapes, some of the more frequently encountered combinations of clouds in the lower and upper formations were examined.

Kh. Urazayeva participated in the work.

1. Scattered Radiation. Table 1 shows the average values of scattered solar radiation intensity for the snow-free period under various conditions at

TABLE 1. AVERAGE VALUES OF THE SCATTERED SOLAR RADIATION (cal/cm^2 min) UNDER VARIOUS CONDITIONS.

Cloudiness: Points	Cloudiness: Form	Sunshine	$h_{\odot}^{\circ}$ 5	10	15	20	25	30	35	40	45	50	55
2—3	Ci, Ci, Cs	$\odot^2$	0,04	0,07	0,10	0,11	0,12	0,12	0,13	0,15	0,16	0,18	0,19
		$\odot$	0,03	0,07	0,10	0,12	0,14	0,16	0,17	0,19	0,20	0,21	
	Ac, Sc	$\odot^2$		0,07	0,10	0,13	0,16	0,17	0,18	0,19	0,20	0,20	
		$(\odot)$	0,04	0,07	0,10	0,13	0,16	0,19	0,21	0,24	0,27		
	Cu	$\odot^2$		0,06	0,08	0,10	0,13	0,14	0,16	0,17	0,18	0,19	0,20
		$(\odot)$	0,04	0,07	0,09	0,12	0,14	0,17	0,19	0,20	0,22	0,23	0,24
	Sc; Ac, Cu	(П)	0,03	0,05	0,08	0,11	0,13	0,16					
4—5	Ci, Ci, Cs	$\odot^2$	0,05	0,07	0,10	0,11	0,13	0,14	0,16	0,17	0,18	0,19	0,20
		$\odot$	0,04	0,08	0,10	0,12	0,14	0,16	0,18	0,19	0,20	0,21	0,22
	Ac, Sc	$(\odot^2)$		0,09	0,11	0,15	0,18	0,21	0,24	0,28	0,29	0,30	0,31
		$(\odot)$	0,03	0,07	0,10	0,14	0,18	0,21	0,24	0,28	0,31	0,34	0,37
	Cu	$\odot^2$			0,10	0,13	0,16	0,19	0,22	0,24	0,27	0,28	0,29
		$(\odot)$		0,07	0,10	0,13	0,16	0,19	0,21	0,23	0,25	0,27	0,29
	Cu; Sc, Ac	(П)	0,03	0,07	0,11	0,14	0,17	0,20	0,22	0,25	0,28	0,30	0,31
6—7	Ci, Ci, Cs	$(\odot^2)$		0,06	0,08	0,11	0,13	0,16	0,17	0,18	0,19	0,20	0,21
		$\odot$	0,04	0,08	0,11	0,13	0,16	0,18	0,21	0,23	0,25	0,26	
	Ac, Sc	$(\odot^2)$		0,08	0,12	0,17	0,21	0,25	0,28	0,30	0,32	0,33	
		$\odot$		0,10	0,14	0,18	0,22	0,28	0,31	0,34	0,36	0,39	0,41
		(П)	0,03	0,09	0,13	0,17	0,21	0,24	0,27	0,29	0,31	0,32	0,33
	Cu	$\odot^2$						0,21	0,24	0,27	0,30	0,32	0,34
		$\odot$			0,14	0,17	0,20	0,23	0,26	0,28	0,31	0,34	0,37
		(П)							0,25	0,28	0,31	0,34	0,36
	Cb with Cu or Sc	$(\odot)$		0,09	0,13	0,18	0,22	0,25	0,29	0,33	0,37	0,39	0,42
		(П)		0,07	0,11	0,14	0,17	0,20	0,22	0,24	0,25	0,28	0,29
8—9	Ci, Ci, Cs	$(\odot^2)$		0,08	0,11	0,15	0,17	0,19	0,21	0,23	0,24	0,25	
		$\odot$	0,05	0,09	0,13	0,17	0,19	0,22	0,25	0,28	0,29	0,31	

Note: Commas in these tables represent decimal points.

Cloudiness: Points	Cloudiness: Form	Sunshine	$h^{\circ}_{\odot}$: 5	10	15	20	25	30	35	40	45	50	55
	Ac , Sc	($\odot^2$)		0,10	0,15	0,19	0,23	0,27	0,33	0,38	0,42	0,47	
		$\odot$	0,04	0,10	0,15	0,20	0,26	0,31	0,37	0,42	0,48	0,53	0,58
	Ac; Ac, Cu , Ac, Sc	П	0,03	0,08	0,12	0,17	0,22	0,26	0,31	0,35	0,40	0,45	0,50
	Sc; Sc, Cu , Sc, Ac	(П)		0,05	0,09	0,14	0,19	0,24	0,29	0,33	0,38	0,42	
	Cu , Cu, Cb	($\odot^2$)	0,05	0,08	0,12	0,16	0,20	0,24	0,28	0,31	0,34	0,38	0,41
		$\odot$			0,14	0,18	0,24	0,30	0,35	0,39	0,42	0,44	0,45
	Cu	(П)						0,22	0,26	0,30	0,34	0,38	0,40
	Cb with Cu or Sc	П	0,03	0,05	0,09	0,13	0,17	0,21	0,25	0,28	0,32	0,34	0,36
10	Ci , Ci, Cs	$\odot$	0,06	0,11	0,15	0,19	0,23	0,27	0,31	0,34	0,37	0,39	0,40
	Cs , Cs, Ci	($\odot$)	0,05	0,10	0,14	0,18	0,23	0,28	0,32	0,36	0,40	0,43	0,46
$\boxed{10}$	Ac, Cu , Sc Cu = Ac, Sc	$\odot$	0,05	0,11	0,17	0,23	0,30	0,36	0,42	0,48	0,54	0,60	0,67
	Ac = Sc	П	0,02	0,06	0,10	0,15	0,21	0,26	0,32	0,37	0,42	0,47	0,52
	Sc, Cu , Sc, Ac	П		0,04	0,09	0,14	0,19	0,24	0,29	0,34	0,39	0,44	0,48
	Cb do not predominate	П		0,06	0,09	0,12	0,17	0,20	0,24	0,28	0,32	0,35	0,39
	Cb predominate	(П)	0,02	0,04	0,08	0,11	0,15	0,18	0,22	0,26	0,30	0,33	0,37
10	Ac; Ac, Sc , Ac, Cu	(П)	0,02	0,06	0,10	0,14	0,19	0,25	0,30	0,35	0,41	0,47	0,53
	Sc	П	0,02	0,04	0,07	0,10	0,14	0,18	0,22	0,25	0,28	0,30	0,31
	Sc, Cu Sc, Ac	П		0,04	0,08	0,12	0,17	0,22	0,27	0,32	0,36	0,41	
	Cb do not predominate	П	0,03	0,05	0,09	0,12	0,16	0,19	0,21	0,24	0,27	0,29	0,32
	Cb predominate	П		0,04	0,07	0,10	0,12	0,14	0,16	0,17	0,19	0,20	0,22
	As	(П)	0,03	0,05	0,06	0,08	0,10	0,14	0,18	0,24	0,32		
	≡	(П)	0,03	0,05	0,08	0,11	0,14	0,16	0,18				
	St	П	0,02	0,04	0,06	0,08	0,10	0,12	0,14	0,16	0,18	0,20	
	Ns	П	0,01	0,03	0,05	0,06	0,08	0,09	0,11	0,12	0,14	0,15	0,16

intervals of 5^{o} solar altitude. The brackets which are used in marking the intensity of solar glow mean that for some intervals of solar altitude the values are approximate.

A comparison of the average values of scattered radiation over individual seasons has shown that only for St, Ns and fog ($\equiv$) can we detect its variation from season to season. With St and Ns a decrease in scattered radiation from spring to summer is observed, which apparently is due to the increase in the density of the cloud cover associated with an increase in its vertical power and liquid water content. In the fall with St scattered radiation has a minimum value, while with Ns it is the same as in the summer. However, during fog in the summer scattered radiation is greater than in other seasons. We may assume that this is due to the lower vertical extent of the summer night inversion compared with other seasons (ref. 3) and also due to a more rapid morning heating of the drier soil. Fogs are observed primarily up to a solar altitude of $25\text{-}30^{o}$.

Table 2 shows correction coefficients which must be used to multiply the data of Table 1 when $h_{\odot} > 10^{o}$, in order to obtain the seasonal characteristics of St, Ns and of the fog.

It is necessary to point out that due to the oscillation of the vertical power and the microstructure of the clouds which have the same form, due to their distribution in the sky and with respect to the sun, and in the case of little cloudiness due to variation in the transparency of the atmosphere when the altitude of the sun and other conditions remain the same, the intensity of scattered radiation may vary within wide limits.

TABLE 2. CORRECTION COEFFICIENTS FOR TAKING INTO ACCOUNT SEASONAL DIFFERENCES IN INTENSITY OF SCATTERED SOLAR RADIATION.

Clouds	Spring	Summer	Autumn
St	1.30	(0.95)	0.80
Ns	1.20	0.90	0.90
$\equiv$	(0.90)	(1.40)	0.90

Due to the great stability of the conditions when the clouds are illuminated with a closed solar disk, the intensity of scattered radiation varies much less than when we have direct solar radiation. When sunshine is moderate ($\odot$), the amplitude of the oscillations of scattered radiation is somewhat greater than in the case of strong sunshine ($\odot^{2}$); this difference is most noticeable when we have clouds which are transparent to direct radiation--Ci and least of all for Cu.

The maximum oscillations of scattered radiation are characteristic of the most powerful clouds--convective clouds. When the sun is shining, scattered radiation is most stable when we have the thinnest clouds--Ci; however, when substantial cloudiness exists (from 8-9 points), as we know, the vertical extent of the upper layer clouds increases and the oscillations of scattered radiation also increase, approaching those observed for Cu and Cb.

When sunshine is absent, scattered radiation is most stable for the thinnest clouds which are opaque for direct radiation--Ac. When we have cloudiness of $\boxed{10}$, and particularly when it is 10 points, the variations in scattered radiation are particularly great: for Sc it is almost the same as for Cb. As we know, the vertical power and the microstructure of Sc may vary, depending on the values characteristic for Ac, to values typical for the lowest clouds--St.

As the number of clouds is increased, the oscillations of scattered radiation generally increase. However, in spite of the noticeable difference in the amplitudes of the oscillations of scattered radiation with different forms, number of clouds and altitudes of the sun, the relative deviations of the maximum values from the average values when cloudiness is less than $\boxed{10}$ points vary little. As a rule, under these conditions the relative deviation of the maximum values from the average values does not exceed 40-50 percent. This is due to the corresponding changes in the average values of radiation. Only for cloudiness of 8-9 and $\boxed{10}$ points does Ci deviation reach 60 percent, while for $\boxed{10}$ Cb, on the average, it reaches 80 percent. In the case of a closed cloud cover (10/10) Cb, Sc and also St and Ns, due to the decrease in the average value of scattered radiation, the deviations approach 100 percent.

The relationship $D = f(h_{\odot})$ is nonlinear, especially when cloudiness is small; however, as the number of clouds increases, it becomes linear.

When solar rays pass through a thin cloud layer ($\odot$), due to variation in the scattering indicatrix, scattered radiation increases with the altitude of the sun at a greater rate than in the case of the open solar disk, and relationship $D = f(h_{\odot})$ is closer to a linear one; this is particularly clear for Ac and Sc (Table 1).

For the same reason the intensity of scattered radiation during moderate sunshine is greater than during strong sunshine, and is particularly noticeable for Ac and Sc and also for Ci. For Ac this effect, on the average, is approximately equivalent to an increase in cloudiness by 2 points.

When the solar disk is closed (Π), scattered radiation differs little from the one observed for the case $\odot^2$.

A comparison of scattered radiation for different clouds, but with all other conditions equal, shows that when we have direct solar radiation ($\odot^2$ and $\odot$) maximum scattered radiation is observed when the clouds have a wavy form (Ac and Sc), while minimum radiation is observed when the clouds are of the upper formation, and for Cs it is slightly greater than for Ci. These results agree with the conclusions of other authors. In this respect conductive clouds occupy an intermediate position; however, when the disk of the sun is open, they vary little from Ac and Sc. As the number of clouds increases, the difference in scattered radiation for different cloud shapes increases (fig. 1).

For the closed disk of the sun, the radiation in the case of wavy clouds is also higher than for convective clouds: the maximum values of these forms, when the cloudiness is 10 points, are characteristic for the thinner clouds (Ac) and are minimum for the most powerful (Cb) (fig. 1).

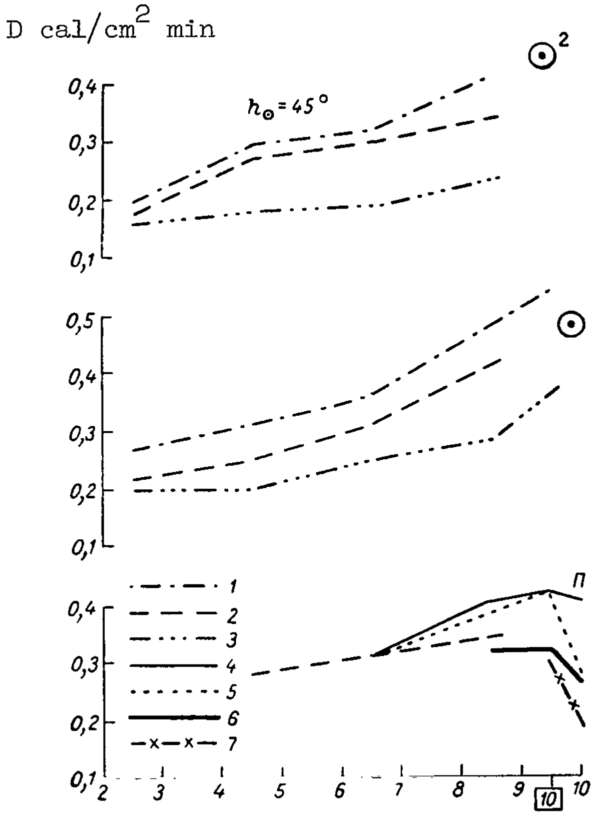

Figure 1. Scattered solar radiation under various conditions of cloudiness and various conditions of the solar disk.

1, Ac and Sc; 2, Cu; 3, Ci and Cs; 4, Ac; 5, Sc, and 6, Cb do not predominate; 7, Cb predominate.

Table 1 shows and figure 1 illustrates that the difference between scattered radiation for Ac and Sc occurs only when we have a closed cloud cover, in which case the characteristics of Sc approach those of St in a series of cases. As shown by observed data, this difference in the average values occurs precisely as a result of the minimum values. However, the maximum values of scattered radiation for Ac and Sc coincide.

The data in Table 1 also show that, when we have cloudiness of 10 points (without clear gaps), scattered radiation for layer-type clouds is less than for other cloud forms of the same formation. Thus, for St, and particularly for Ns, scattered radiation is much less than for Sc and even Cb. This difference in the average values is due to the lower maximum values. Only when we have fog, at low altitudes of the sun, does scattered radiation become greater than for Sc, op and Cb. For As op, scattered radiation is much less than for Ac op. For low altitudes of the sun it is less than the one observed for Sc and fog.

The results obtained convince us that in studying scattered radiation we cannot combine clouds of one layer which differ in their shape and vertical power, and that from the standpoint of their effect on the intensity of scattered radiation, the clouds of the middle layer differ little from the clouds of the lower layer which are isomorphic. These results confirm completely the conclusions obtained earlier (ref. 5) by analyzing the relationships of actual diurnal sums of radiation possible for various clouds.

By investigating the effect of the number of clouds on scattered radiation, we may conclude that for any cloud shapes and intensity of sunlight, the increase in the cloudiness point to the mark $\boxed{10}$ leads to a continuous increase in scattered radiation (fig. 1). Only for the more powerful clouds (Cb) the increase in cloudiness from 8-9 to 10 points does not produce an increase in scattered radiation. When clear gaps vanish in the clouds (mark $\boxed{10}$), scattered radiation decreases, with particular rapidity for Sc and Cb (predominately).

If for Cb this is due to the sharp decline in the illumination of the clouds by direct solar radiation, then for Sc it is evident that the principal role is played by the mentioned difference in the vertical power and altitude of Sc trans. and Sc op.

From available data in the literature (refs. 1 and 10), the continuous increase in scattered radiation with increase in the number of clouds is characteristic only for clouds of the upper layer, while for clouds of other layers the maximum values of scattered radiation refer to a cloudiness of 8 points. This contradiction of our results with the conclusions of other authors is explained by the fact that observations have usually been processed not over individual cloud shapes, but on an average basis for each layer. Since convective and particularly layer-like clouds give lower values for scattered radiation than wavy clouds, this averaging led to the reduction in the average values of radiation under conditions of considerable cloudiness. In addition, observations during cloudiness $\boxed{10}$ and 10 were considered together.

As we can see from the data in Table 1, the highest and lowest values of scattered solar radiation are observed when cloudiness is 10 points: maximum for $\odot$ $\boxed{10}$ Ac and Sc, and minimum for Ns.

Let us consider some specific problems which follow from the data of Table 1. We see for example that for the designation $\boxed{10}$, scattered radiation, when we correlate Sc, Cu and Ac, Cu, is smaller on the average than for individual Sc or

Ac, which is due to the great density of the double layer cloudiness. However, when the cloudiness designation is 10 points (without clear gaps), scattered radiation of these combinations is greater than for Sc; apparently this is explained by the fact that Cu may be observed under the Sc layer only when the altitude of the bases is high and, consequently, when the vertical power of the latter is less.

We may also point out that when cloudiness is less than 6-7 points, the individual observations, when Cb is present (usually Cu, Cb), give values for scattered radiation which differ from those observed for Cu; however, starting with 6-7 points, scattered radiation, when the sun is covered by Cb, is less than for less dense clouds Cu (see Table 1). But when the sun is shining, scattered radiation for Cb is greater than for Cu, which apparently is associated with the crystalline structure of the apexes of Cb. Therefore, with Cb we obtain sharper variations in scattered radiation when we go from designation ⊙ to designation П.

Due to the different methodologies used in processing the data, it is difficult to compare the values of scattered radiation obtained by us with the results of other authors. Table 3 shows the average values of scattered radiation, when cloudiness is 10 points, for several clouds according to the data obtained with the Yanishevskiy pyranometer at Pavlovsk (N. N. Kalitin) and at Karadagh (Ye. P. Barashkova).

The works of Ye. P. Barashkova (refs. 1 and 2) do not indicate the form of the data for Ac and Sc (opacus or translucidus). From the work of N. N. Kalitin (ref. 6) we may conclude that for Ac there was direct radiation, while for Sc it did not exist, because in Table 3 for Ac we introduced the average weighted value of scattered radiation obtained by taking into account the recurrence of designations 10, $\boxed{10}$ П and $\boxed{10}$ ⊙, while for Sc we took into account the recurrence of designations 10 and $\boxed{10}$ П.

TABLE 3. AVERAGE VALUES OF SCATTERED SOLAR RADIATION (cal/cm^2 min) WITH CLOUDINESS OF 10 POINTS ACCORDING TO DATA OF N. N. KALITIN (K), YE. P. BARASHKOVA (B), B. M. GAL'PERIN AND L. P. SERYAKOVA (GS).

Clouds	10°			20°			30°			40°			50°		
	K	B	GS	K	B	GS	K	B	GS	K	B	GS	K	B	GS
Ci	0,09	—	0,11	0,16	—	0,19	0,22	—	0,27	0,26	—	0,34	0,29	—	0,39
Cs	0,11	0,10	0,10	0,19	0,19	0,18	0,27	0,27	0,28	0,34	0,34	0,36	0,40	0,38	0,43
Ac	0,09	0,10	0,08	0,22	0,22	0,17	0,31	0,32	0,29	0,39	0,40	0,40	0,44	0,56	0,51
As	0,09	—	0,05	0,17	—	0,08	0,24	—	0,14	0,30	—	0,24	0,35	—	—
Sc	0,04	0,08	0,04	0,13	0,15	0,11	0,20	0,21	0,20	0,27	0,27	0,27	0,33	0,36	0,34
St	0,04	0,08	0,04	0,08	0,14	0,08	0,13	0,20	0,12	0,16	0,33	0,16	0,19	0,52	0,20

We can see that in the majority of cases the values obtained by us are close to the results of other authors. Some discrepancies may be due to the difference in the methodology for determining them. Thus, e.g., the higher values of scattered radiation for Ci, and to a lesser extent for Cs, according to our data, apparently are due to the fact that they refer only to the designation $\odot$; in addition, the observations for Ci and Ci, Cs are combined. It is doubtful that the high values for St presented in the work of Ye. P. Barashkova are associated only with the climatological peculiarities of the maritime observation point--Karadagh; attention is drawn to their irregular variation with solar altitude. The difference between the values for scattered radiation obtained by us and by N. N. Kalitin for As is explained by the fact that they refer to various forms: in our case they referred to the form opacus while in the case of N. N. Kalitin they referred to translucidus.

2. Total Solar Radiation. Table 4 shows the average values of total solar radiation during the snow-free period for a clear sky Q_0, for various cloudiness, and various intensity of sunlight. As we can see from figure 2, the noticeable time variations in Q_0, which are due to the corresponding variations in transparency of the atmosphere, take place only during transition from one season to another, while during the three summer months the average monthly values of Q_0 are sufficiently constant. In July Q_0 constitutes 97 percent of the average value for the snow-free period, while in April and October it is, respectively, 106 and 103 percent. These variations in the transparency of the atmosphere are also due to the fact that for small cloudiness (2-3 and 4-5 points) the average summer values of the total radiation for designations $\odot^2$ and $\odot$ are less than the spring-summer values. Since in the summer the number of observations under this cloudiness is greater than in other seasons, the difference of the summer quantities from the average value, for the entire period, even for high altitudes of the sun, generally does not exceed 0.02 cal/cm^2 min. The spring-autumn values of the total radiation are above the average values: for $h_\odot = 30°$ by not greater than 0.02-0.03, while for $h_\odot = 50°$ by 0.06-0.07 cal/cm^2 min.

A comparison of empirical graphs $D = f(h_\odot)$ and $Q = f(h_\odot)$ has shown that not only for the open disk of the sun, but also for small cloudiness even when sunlight is moderate, the oscillations of total radiation for a constant solar altitude and other equal conditions are due basically to the variations in scattered solar radiation. The effect of variation in the direct radiation is clearly manifested, even when cloudiness is 6-7 points ($\odot$) for Ci and Ac. For 8-9 points it is also high for Cu. The greatest variation in total solar radiation takes place when cloudiness is 10 points in the upper layer. For designation $\odot^0$, the oscillations of radiation are substantially less than for designations $\odot^2$ and $\odot$.

TABLE 4. AVERAGE VALUES OF TOTAL SOLAR RADIATION (cal/cm^2 min) FOR VARIOUS CONDITIONS.

Clouds: Points	Clouds: Form	Sunshine	$h^\circ_\odot$ 5	10	15	20	25	30	35	40	45	50	55
0/0	—	$\odot^2$	0,07	0,18	0 31	0,43	0,55	0,66	0,79	0,90	1,01	1,11	1,20
2—3	Ci, Ci, Cs	$\odot^2$	0,07	0,17	0,30	0,42	0,55	0,68	0,80	0,90	1,00	1,10	1,18
		$\odot$	0,05	0,14	0,27	0,40	0,52	0,65	0,77	0,88	0,98	1,06	
	Ac, Sc	$\odot^2$	0,06	0,17	0,29	0,40	0,53	0,65	0,76	0,88	1,00	1,11	1,23
		$\odot$	0,06	0,16	0,28	0,39	0,51	0,63	0,74	0,86	0,97		
	Cu	$\odot^2$		0,16	0,29	0,42	0,55	0,67	0,80	0,93	1,03	1,14	1,24
		$(\odot)$		0,16	0,29	0,42	0,54	0,66	0,79	0,92	1,02	1,11	1,20
4—5	Ci, Ci, Cs	$\odot^2$		0,17	0,29	0,42	0,55	0,67	0,78	0,89	1,00	1,10	1,20
		$\odot$	0,06	0,16	0,28	0,40	0,52	0,64	0,76	0,87	0,98	1,08	1,18
	Ac, Sc	$\odot^2$	0,07	0,18	0,32	0,44	0,56	0,69	0,82	0,95	1,08	1,18	
		$(\odot)$	0,07	0,18	0,30	0,42	0,54	0,66	0,78	0,90	1,02	1,13	1,24
	Cu	$\odot^2$		0,19	0,31	0,44	0,56	0,69	0,82	0,96	1,09	1,21	1,30
		$\odot$		0,18	0,30	0,43	0,55	0,69	0,82	0,94	1,06	1,16	1,26
	Cu; Ac, Sc	$(\odot^\circ)$			0,13	0,17	0,21	0,24	0,28	0,31	0,35	0,39	0,43
6—7	Ci, Ci, Cs	$(\odot^2)$		0,17	0,29	0,43	0,55	0,68	0,80	0,91	1,02	1,12	1,21
		$\odot$	0,06	0,15	0,26	0,37	0,48	0,60	0,71	0,83	0,94	1,05	1,17
	Ac, Sc	$(\odot^2)$	0,07	0,20	0,32	0,45	0,58	0,70	0,82	0,95	1,08	1,20	1,32
		$\odot$		0,20	0,32	0,43	0,55	0,67	0,79	0,90	1,02	1,14	1,26
		$(\odot^\circ)$		0,12	0,17	0,23	0,28	0,33	0,38	0,43	0,48		
	Cu, Cu, Cb	$\odot^2$		0,19	0,31	0,44	0,58	0,73	0,87	1,01	1,14	1,25	1,34
		$(\odot)$		0,17	0,30	0,43	0,56	0,70	0,83	0,96	1,10	1,21	1,30
		$(\odot^\circ)$		0,12	0,16	0,20	0,24	0,28	0,32	0,36	0,40	0,44	0,48

Clouds: Points	Clouds: Form	Sunshine	$h_{\odot}^{\circ}$: 5	10	15	20	25	30	35	40	45	50	55
8—9	Ci, Ci, Cs	$(\odot^2)$		0,18	0,30	0,42	0,54	0,66	0,78	0,90	1,02	1,14	1,26
		$\odot$	0,07	0,16	0,26	0,39	0,51	0,63	0,74	0,85	0,94	1,04	1,13
		$(\odot^{\circ})$			0,13	0,18	0,25	0,31	0,38	0,45	0,52		
	Ac, Sc	$(\odot^2)$		0,20	0,35	0,50	0,65	0,80	0,94	1,10	1,25	1,36	1,44
		$\odot$	0,07	0,17	0,27	0,39	0,41	0,64	0,76	0,89	1,02	1,14	1,27
		$(\odot^{\circ})$		0,10	0,16	0,21	0,27	0,33	0,39	0,45	0,50	0,56	0,62
	Cu, Cu, Cb Cu	$(\odot^2)$								1,05	1,20	1,32	1,42
		$\odot$					0,66	0,78	0,90	1,03	1,17	1,29	1,42
	Cb with Cu, Sc	$\odot^{\circ}$				0,20	0,24	0,29	0,33	0,38	0,42	0,47	0,51
$\boxed{10}$	Ci, Ci, Cs	$\odot$	0,06	0,15	0,25	0,35	0,46	0,56	0,66	0,77	0,86	0,94	0,98
10	Cs, Cs, Cs	$(\odot)$	0,06	0,14	0,24	0,34	0,45	0,55	0,66	0,74	0,79	0,84	0,88
		$(\odot^{\circ})$	0,04	0,09	0,16	0,22	0,28	0,34	0,41	0,47			
$\boxed{10}$	Ac, Sc	$(\odot)$	0,06	0,16	0,27	0,38	0,48	0,59	0,69	0,80	0,93	1,04	
$\boxed{10}$	Cb with Cu, Sc	$\odot^{\circ}$		0,10	0,15	0,21	0,27	0,32	0,38	0,43	0,48	0,53	0,58
10	Ac, Ac, Cu	$(\odot^{\circ})$				0,19	0,28	0,37	0,45	0,53	0,60	0,67	
	Sc, Sc, Cu	$(\odot^{\circ})$				0,19	0,24	0,29	0,35	0,42	0,49	0,55	

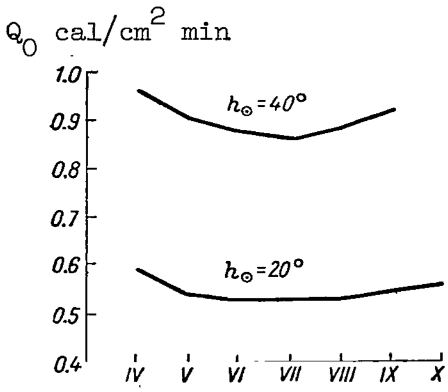

Figure 2. Variation of average values of total solar radiation cloudless sky Q_0 from month to month.

Since the average value of total radiation for the case of moderate and strong sunshine is much higher than that of scattered radiation, the relative values of the oscillations are less. Thus, with a cloudiness up to 8 points, the deviations of the maximum values from the average values do not exceed 15 percent, while for 8-9 points they do not exceed 30 percent and for 10 points Ci and Cs they do not exceed 40 percent.

Both for the case of the cloudless sky and for the case when clouds are present, the relationship $Q = f(h_\odot)$ in the interval $8^\circ < h_\odot < 50^\circ$ is linear.

When $h_\odot > 50^\circ$, we have a retarded increase in total radiation as the solar altitude is increased.

Due to the attenuation of direct solar radiation, the influx of total radiation under conditions of moderate sunshine is less than when the sunshine is strong but, due to the increase in scattered radiation, the lowering of the average values Q is relatively small, particularly for Cu for which the increase of scattered radiation is least noticeable. Apparently this is due to the fact that dense clouds and the designation ⊙ are used only when the edge of the cloud touches the solar disk. Indeed, direct solar radiation for designation (⊙) for Cu is greater than for other clouds.

When we go from moderate to weak sunshine, there is a sharp decrease in the average values of total radiation: further decrease in the influx of solar radiation which occurs during the total screening of the solar disk is no longer large (fig. 3).

Comparing the values of total radiation for various clouds, we may conclude that in accordance with the results obtained for scattered radiation in the case of moderate and strong sunshine, the minimum values are characteristic for Ci. Due to the large decrease in direct radiation, total radiation for the designation ⊙ Ac (Sc) is less than for Cu (fig. 3).

It is difficult to explain why during the open solar disk total radiation for Cu is greater than for Ac, although scattered radiation is smaller. The

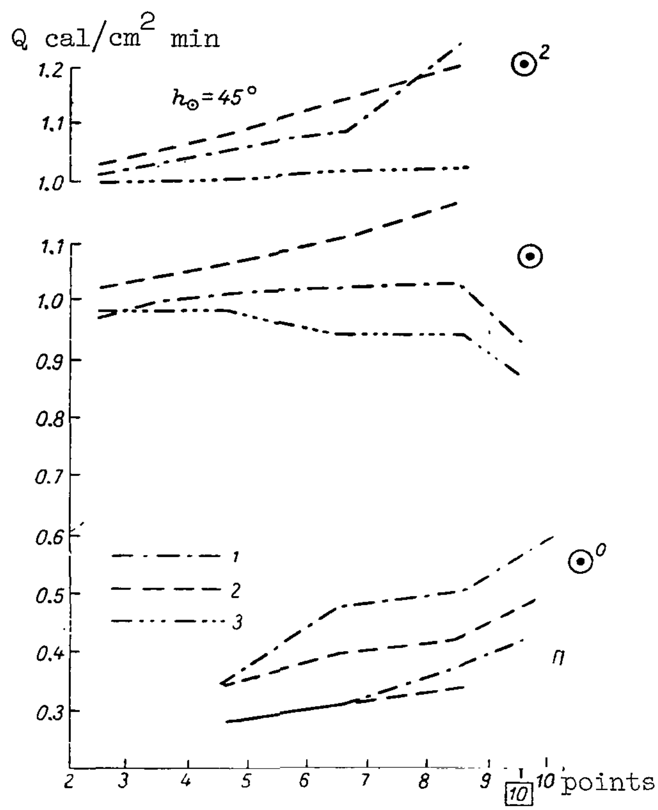

Figure 3. Total solar radiation under various conditions of cloudiness and various states of solar disk.

1, Ac and Sc; 2, Cu; 3, Ci and Cs.

inverse relationship occurs only for small solar altitudes, but the difference is small. We may assume that during the days with subinversion cloudiness (Ac, Sc), the transparency of the atmosphere is somewhat lower. During weak sunshine when the principal role is played by scattered radiation, total radiation for wavy clouds is greater than for convective clouds.

In considering the question on the effect of the number of clouds on total solar radiation, we can see that, in connection with the increase in scattered radiation, total solar radiation under conditions of strong sunlight increases as the amount of cloudiness increases. However, for clouds of the upper layer this increase takes place more slowly than that of scattered radiation. The reason for this may be the decrease in transparency of the atmospheric layer over the frontal surface when the latter is descending.

When sunshine is moderate, the continuous increase in total radiation as the number of clouds increases (with all other conditions being equal) is observed only for Cu. For Ac (Sc) the small increase in total radiation with increase in cloudiness takes place for $h_{\odot} \leq 40°$ up to 6-7 points, and then its decrease is observed. For $h_\odot > 40^\circ$ decrease in radiation starts with 8-9 points, which apparently is due to the smaller attenuation of direct solar radiation in the cloud layer when solar altitudes are high.

In the case of upper layer clouds, for all solar altitudes, even with a cloudiness of 6-7 points, radiation is less than for 4-5 points, but its most noticeable decrease takes place during transition from 8-9 to 10 points. When sunshine is weak, scattered radiation predominates and the increase in the number of clouds brings about an increase in total radiation.

The data of Table 4 and figure 3 show that when the solar disk is open and there is considerable cloudiness Cu or Ac (Sc), total radiation may be 20 percent greater than radiation during the cloudless sky.

For cumulus clouds, even for moderate sunshine, total radiation is greater than for the cloudless sky. For Ac (Sc) only when cloudiness is 6-7 points $Q = Q_0$, while for Ci and Ci, Cs for any number of clouds with designation $\odot$, $Q < Q_0$; however, when we have cloudiness of 10 points even under these conditions the influx of radiation for Ac (Sc) $\odot$ is 91 percent on the average, while for Ci and Ci, Cs it is 84 percent of the radiation with a cloudless sky.

Since the observations during various intensities of sunshine were considered separately, the possibility of comparing the data in Table 4 with the results of other authors is limited. Simple averaging of the values obtained for various designations on the state of the solar disk will not reflect the actual average conditions, because the recurrence of these designations varies. We can only say that the magnitude of total radiation for the cloudless sky which we obtained is very close to the average values of Q_0 obtained by Ye. P. Barashkova from observation data at many stations of the USSR (ref. 2); the values of Q_0 presented in the work of N. N. Kalitin (ref. 6) exceeds them, particularly for large solar altitudes. This is also true in regard to the values of total radiation for Ci when $h_\odot > 30^\circ$; for lower solar altitudes the reverse relationship is obtained. Apparently, the latter is the cause for the large variation in Q_{10}/Q_0 as a function of solar altitude for clouds of the upper layer, according to Kalitin. This relationship has been noted by us previously (ref. 5).

On the basis of the results of the present work it was of interest to establish the degree to which the variation in Q_{10}/Q_0 increases with solar altitude under various conditions. This question is of independent interest because Q_{10}/Q_0 is used to compute the sums of solar radiation.

We can see from Table 5 that for the same designation $\odot$ the quantities Q_{10}/Q_0 for clouds of the upper layer do not exhibit any definite variation with

TABLE 5. VALUES OF Q_{10}/Q_0 % IN PRESENCE OF VARIOUS CLOUDS AND FOR VARIOUS STATES OF SOLAR DISK

Clouds		Sunshine	$h^{\circ}_{\odot}$						
Points	Form		5	10	15	20	30	40	50
$\boxed{10}$	Ci and Ci, Cs	$\odot$	86	83	80	81	87	85	85
10	Cs and Cs, Ci	$(\odot)$	86	78	77	79	83	82	76
$\boxed{10}$	Ac and Sc	$(\odot)$	86	89	87	88	89	89	93
	Cs and Ci	$(\odot^{o})$	-	50	51	51	52	52	-
	Ac and Ac, Cu	$(\odot^{o})$	-	-	-	49	56	59	60
	Sc and Sc, Cu	$(\odot^{o})$	-	-	-	43	44	47	49
	Ac = Sc	Π	43	33	32	35	39	41	42
10	Sc	Π	43	22	23	23	27	28	27
	St	Π	29	22	19	19	18	18	18
	Ns	Π	14	17	16	14	14	13	14
	Cb prevail	Π	-	22	23	23	21	20	19
	$\equiv$	(Π)	43	28	26	26	24		

solar altitude. This does not contradict the conclusions of B. Haurwitz (ref. 9), concerning the fact that for Ci and Cs Q_{10}/Q_0 increases with an increase in solar altitude; observations for designations $\odot$ and $\odot^{o}$ were not separated by him, whereas for low solar altitudes the recurrence of the latter increases.

The variation in Q_{10}/Q_0 as a function of solar altitude is relatively small, even when direct solar radiation is absent (Π). For denser clouds there is even a decrease in Q_{10}/Q_0 as the solar altitude increases. The same effect is obtained if we use the data of Kalitin for St (Ns + St) and also of B. Haurwitz for Ns and for fog.

The small increase in Q_{10}/Q_0 with increase in solar altitude takes place when we have wavy clouds (Ac and Sc), both for weak sunshine and when it is absent. It is possible that this is due to improvement in the illumination of the edges of individual cloud elements as the solar altitude increases, which thereby increases scattered radiation. The same result may be detected by analyzing the data of N. N. Kalitin and B. Haurwitz.

The values obtained in the present work may be used to evaluate the intensity of total and scattered radiation during the snow-free period for various meteorological conditions.

REFERENCES

1. Barashkova, Ye. P. Scattered Radiation at Karadagh (Rasseyannaya radiatsiya v Karadage). Trudy GGO, No. 80, 1959.

2. Barashkova, Ye. P., Gayevskiy, V. L., Pirovarova, Z. I., et al. The Radiation State of the Territory of the USSR (Radiatsionnyy rezhim territorii SSSR). Gidrometeoizdat, Leningrad, 1961.

3. Vorontsov, P. A. The Magnitudes of the Vertical Temperature Gradient in the Boundary Layer of the Atmosphere over Some Base Surfaces (Velichiny vertikal'nogo temperaturnogo gradiyenta v pogranichnom sloye atmosfery nad nekotorymi podstilayushchimi poverkhnostyami). Trudy GGO, No. 63, 1956.

4. Gal'perin, B. M. Total and Scattered Radiation in the Arctic (O summarnoy i rasseyannoy radiatsii v Arktike). Trudy AANII, No. 229, 1961.

5. --- Diurnal Influx of Total Radiation in the Presence of Various Clouds (Sutochnyy prikhod summarnoy solnechnoy radiatsii pri razlichnykh oblakakh). Trudy GGO, No. 125, 1962.

6. Kalitin, N. N. Total Radiation at Pavlovsk (Summarnaya radiatsiya v Pavlovske). Trudy GGO, Issue 19, 1950.

7. --- Actinometry (Aktinometriya). Gidrometeoizdat, Moscow, 1938.

8. Temnikova, N. S. Scattered Radiation of the Sky in Connection with the Shape of Clouds (Rasseyannaya radiatsiya nebesnogo svoda v svyazi s formami oblakov). Meteorologiya i gidrologiya, No. 5, 1941.

9. Haurwitz, B. Insolation in Relation to Cloud Type. Journal of Meteorology, Vol. 5, No. 3, 1948.

10. Dirmhirn, I. Investigations of Solar Radiation in the Eastern Alps (Untersuchungen über die Himmel-Strahlung in den Ostalpen). Archiv für Meteorologie, Geophysik und Bioklimatologie, Vol. 2, No. 4, 1951.

Translated for the National Aeronautics and Space Administration by John F. Holman and Co. Inc.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

TECHNICAL REPRINTS: Information derived from NASA activities and initially published in the form of journal articles.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546